SWITCHING POWER CONVERTER AND METHOD OF CONTROLLING OUTPUT VOLTAGE THEREOF USING PREDICTIVE SENSING OF MAGNETIC FLUX

CROSS-REFERENCE TO RELATED APPLICATION

This application is related to U.S. provisional application Ser. No. 60/482,580, filed June 25, 2003 and from which it claims benefits under 35 U.S.C. §119(e).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to power supplies, and more specifically to a method and apparatus for controlling a switching power converter entirely from the primary side of the power converter by predictive sensing of magnetic flux in a magnetic element.

2. Background of the Invention

Electronic devices typically incorporate low voltage DC power supplies to operate internal circuitry by providing a constant output voltage from a wide variety of input sources. Switching power converters are in common use to provide a voltage regulated source of power, from battery, AC line and other sources such as automotive power systems.

Power converters operating from an AC line source (offline converters) typically require isolation between input and output in order to provide for the safety of users of electronic equipment in which the power supply is included or to which the power supply is connected. Transformer-coupled switching power converters are typically employed for this function. Regulation in a transformer-coupled power converter is typically provided by an isolated feedback path that couples a sensed representation of an output voltage from the output of the power converter to the primary side, where an input voltage (rectified line voltage for AC offline converters) is typically switched through a primary-side transformer winding by a pulse-width-modulator (PWM) controlled switch. The duty ratio of the switch is controlled in conformity with the sensed output voltage, providing regulation of the power converter output.

The isolated feedback signal provided from the secondary side of an offline converter is typically provided by an optoisolator or other circuit such as a signal transformer and chopper circuit. The feedback circuit typically raises the cost and size of a power converter significantly and also lowers reliability and long-term stability, as optocouplers change characteristics with age.

An alternative feedback circuit is used in flyback power converters in accordance with an embodiment of the present invention. A sense winding in the power transformer provides an indication of the secondary winding voltage during conduction of the secondary side rectifier, which is ideally equal to the forward drop of the rectifier added to the output voltage of the power converter. The voltage at the sense winding is equal to the secondary winding voltage multiplied by the turns ratio between the sense winding and the secondary winding. A primary power winding may be used as a sense winding, but due to the high voltages typically present at the power winding, deriving a feedback signal from the primary winding may raise the cost and complexity of the feedback circuit. An additional low voltage auxiliary winding that may also be used to provide power for the control and feedback circuits may therefore be employed. The above-described technique is known as "magnetic flux sensing" because the voltage present at the sense winding is generated by the magnetic flux linkage between the secondary winding and the sense winding.

Magnetic flux sensing lowers the cost of a power supply by reducing the number of components required, while still providing isolation between the secondary and primary sides of the converter. However, parasitic phenomena typically associated

with magnetically coupled circuits cause error in the feedback signal that degrade voltage regulation performance. The above-mentioned parasitics include the DC resistance of windings and switching elements, equivalent series resistance (ESR) of filter capacitors, leakage inductance and non-linearity of the power transformer and the output rectifier.

Solutions have been provided in the prior art that reduce the effect of some of the above-listed parasitics. For example, adding coupled inductors in series with the windings or a leakage-spike blanking technique reduce the effect of leakage inductance in flyback voltage regulators. Other techniques such as adding dependence on the peak primary current (sensed switch current) to cancel the effect of the output load on sensed output voltage have been used. However, the on-resistance of switches typically vary greatly from device to device and over temperature and the winding resistances of both the primary and secondary winding also vary greatly over temperature. The equivalent series resistance (ESR) of the power converter output capacitors also varies greatly over temperature. All of the above parasitic phenomena reduce the accuracy of the above-described compensation scheme.

In a discontinuous conduction mode (DCM) flyback power converter, in which magnetic energy storage in the transformer is fully depleted every switching cycle, accuracy of magnetic flux sensing can be greatly improved by sensing the voltage at a constant small value of magnetization current while the secondary rectifier is still conducting. However, no prior art solution exists that provides a reliable and universal method that adapts to the values of the above-mentioned parasitic phenomena in order to accurately sense the voltage at the above-mentioned small constant magnetization current point in DCM power converters.

Therefore, it would be desirable to provide a method and apparatus for controlling a power converter output entirely from the primary, so that isolation bridging is not required and having improved immunity from the effects of parasitic phenomena on the accuracy of the power converter output.

SUMMARY OF THE INVENTION

The above objective of controlling a switching power converter output entirely from the primary side with improved immunity from parasitic phenomena is achieved in a switching power converter apparatus and method. The power converter includes an integrator that generate a voltage corresponding to magnetic flux within a power magnetic element of the power converter. The integrator is coupled to a winding of the power magnetic element and integrates the voltage of the winding. A detection circuit detects an end of a half-cycle of post-conduction resonance that occurs in the power magnetic element subsequent to the energy level in the power magnetic falling to zero. The voltage of the integrator is stored at the end of a first post-conduction resonance half-cycle and is used to determine a sampling time prior to or equal to the start of a post-conduction resonance in a subsequent switching cycle of the power converter. At the sampling time, the auxiliary winding voltage is sampled and used to control a switch that energizes the power magnetic element.

The foregoing and other objectives, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the

invention, as illustrated in the accompanying drawings, wherein like reference numerals indicate like components throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of a power converter in accordance with an embodiment of the present invention.

Figure 1B is a schematic diagram of a power converter in accordance with an alternative embodiment of the present invention.

Figure 2 is a waveform diagram depicting signals within the power converters of **Figures 1** and **1B**.

Figure 3 is a schematic diagram of a power converter in accordance with another embodiment of the present invention.

Figure 4 is a schematic diagram of a power converter in accordance with yet another embodiment of the present invention.

Figure 5 is a waveform diagram depicting signals within the power converters of **Figures 3** and **4**.

Figure 6 is a schematic diagram of a power converter in accordance with yet another embodiment of the present invention.

Figure 7 is a schematic diagram depicting details of an ESR-compensated control circuit in accordance with an embodiment of the present invention.

Figure 8 is a schematic diagram depicting details of an ESR-compensated control circuit in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The present invention provides novel circuits and methods for controlling a power supply output voltage using predictive sensing of magnetic flux. As a result, the line and load regulation of a switching power converter can be improved by incorporating one or more aspects of the present invention. The present invention includes, alone or in combination, a unique sampling error amplifier with zero magnetization detection circuitry and unique pulse width modulator control circuits.

Figure 1 shows a simplified block diagram of a first embodiment of the present invention. The switching configuration shown is a flyback converter topology. It includes a transformer **101** with a primary winding **141**, a secondary winding **142**, an auxiliary winding **103**, a secondary rectifier **107** and a smoothing capacitor **108**. A resistor **109** represents an output load of the flyback converter. A capacitor **146** represents total parasitic capacitance present at an input terminal of primary winding **141**, including the output capacitance of the switch **102**, inter-winding capacitance of the transformer **101** and other parasitics. Capacitance may be added in the form of additional discrete capacitors if needed in particular implementations for lowering the frequency of the post-conduction resonance condition. The

power converter of **Figure 3** also includes an input terminal **147**, a supply voltage terminal **143** which is a voltage derived from auxiliary winding **103** by means of a rectifier **113** and a smoothing capacitor **112**, a feedback terminal **144**, and a ground terminal **145**. Voltage **VIN** at the input terminal **147** is an unregulated or poorly regulated DC voltage, such as one generated by the input rectifier circuitry of an offline power supply. The power converter also includes a power switch **102** for switching current through the primary winding **141** from input terminal **147** to ground terminal **145**, a sample-and-hold circuit **124** connected to feedback terminal **144** via a resistive voltage divider formed by resistors **110** and **111**, an error amplifier circuit **123** having one of a pair of differential inputs connected to an output of sample-and-hold circuit **124** and having another differential input connected to a reference voltage **REF**, a pulse width modulator circuit **105** that generates a pulsed signal having a duty ratio as a function of an output signal of error amplifier circuit **123**, a gate driver **106** for controlling on and off states of power switch **102** in accordance with the output of the pulse width modulator circuit **105**, an integrator circuit **128** having an input connected to feedback terminal **144** and a reset input, a differentiator circuit **127** having an input connected to feedback terminal **144**, a zero-derivative detect comparator **126** having a small hysteresis and having one of a

pair or differential inputs connected to the output of differentiator circuit **127**, and another differential input connected to an offset voltage source **131**, a blanking circuit **134** for selectively blanking the zero-derivative detect comparator **126** output, a sample-and-hold circuit **129** controlled by the output signal of the comparator **126** via the blanking circuit **134** for selective sampling-and-holding the output signal of the integrator circuit **128**; a comparator **125** having one of a pair of differential inputs connected to the output of sample-and-hold circuit **129** and offset by a voltage source **130**, and another differential input connected to the output of integrator circuit **128**. The output of comparator **125** controls the sample-and-hold circuit **124**.

Referring now to **Figure 1B**, a forward power converter in accordance with an alternative embodiment of the present invention is depicted. Rather than auxiliary winding **103** being provided as a transformer winding, in the present embodiment, the feedback signal is provided by auxiliary winding **103** of an output filter inductor **145**. A free-wheeling diode **199** is added to the circuit to return energy from a power winding **198** of output filter inductor **145**, to capacitor **108** and load **109**. When switch **102** is enabled, a secondary voltage of positive polarity appears across winding **142** equal to input voltage VIN divided by

turn ratio between windings **141** and **142**. Diode **107** conducts, coupling the power winding of inductor **198** between winding **142** and filter capacitor **108**. Energy is thereby stored in inductor **198**. When switch **102** is disabled, diode **107** becomes reverse biased, and diode **199** conducts, returning energy stored in inductor **198** to output filter capacitor **108** and load **109**. When the magnetic energy stored in inductor **198** fully depleted, inductor **198** enters post-conduction resonance (similar to that of transformer **101** in the circuit of **Figure 1**). Therefore, auxiliary winding **103** provides similar waveforms as the circuit of **Figure 1** and provides a similar voltage feedback signal that are used by the control circuit of the present invention.

Operation of the circuits of **Figures 1** and **1B** is depicted in the waveform diagram of **Figure 2**, respecting the difference that auxiliary winding **103** of **Figure 1B** is provided on output filter inductor **198**. Referring additionally to **Figure 2**, at time **Ton**, power switch **102** is turned on. During the period of time between **Ton** and **Toff**, a linear increase of the magnetization current in primary winding **141** of flyback transformer **101** occurs. A voltage **201** of negative polarity and proportional to the input voltage **VIN** as determined by the turns ratio between auxiliary winding **103** and primary winding **141** will appear at feedback terminal **144**. (In the circuit of **Figure 1B**, the

feedback voltage is proportional to the difference between **VIN** divided by the turn ratio between windings **141** and **142** and the output voltage across capacitor **108.**) The feedback terminal **144** voltage causes a linear increase in the output voltage **202** of integrator **128.** The duration of the on-time of the power switch **102** is determined by the magnitude of the error signal at the output of error amplifier **123.**

At time **Toff**, power switch **102** is turned off, interrupting the magnetization current path of primary winding **141** (or the power winding of inductor **198** in the circuit of **Figure 1B**). Secondary rectifier **107** (or diode **199** in the circuit of **Figure 1B**) then becomes forward biased and conducts the magnetization current of secondary winding **142** (or the power winding of inductor **198** in the circuit of **Figure 1B**) to output smoothing capacitor **108** and load **109.** The magnetization current decreases linearly as the flyback transformer **101** (or inductor **198** in the circuit of **Figure 1B**) transfers energy to output capacitor **108** and load **109.** A positive voltage **201** is then present at feedback terminal **144** (and similarly for the circuit of **Figure 1B** after diode **107** ceases conduction and diode **199** conducts), having a voltage proportional to the sum of the output voltage across capacitor **108** and the forward voltage of rectifier **107** (or diode **199** in the circuit of **Figure 1B**) and the proportion is

determined by the turn ratio between auxiliary winding **103** and secondary winding **142** (or power winding **198** in the circuit of **Figure 1B**). The feedback terminal **144** voltage causes the output voltage of integrator **128** to decrease linearly until, at time **To**, transformer **101** (or output filter inductor **198** in the circuit of **Figure 1B**) is fully de-energized. At time **To**, rectifier **107** (or diode **199** in the circuit of **Figure 1B**) becomes reverse biased, and the voltage across the windings of the transformer **101** (or inductor **198** in the circuit of **Figure 1B**) reflects a post-conduction resonance condition as shown.

The period of the post-conduction resonance is a function of the inductance of primary winding **141** and parasitic capacitance **146** (or the parasitic capacitance as reflected at the power winding of filter inductor **198** in the circuit of **Figure 1B**). Differentiator circuit **127** continuously generates an output corresponding to the derivative of voltage **201** at feedback terminal **144**. The output of differentiator **127** is compared to a small reference voltage **131** by comparator **126**, in order to detect a zero-derivative condition at feedback terminal **144**. Comparator **126** provides a hysteresis to eliminate its false tripping due to noise at the feedback terminal **144**. Output voltage **202** of integrator **128** is sampled at time **T2**, when comparator **126** detects the zero-derivative condition at feedback

terminal **144** (positive edge of comparator **126** output **204**). Blanking circuit **134** disables the output of comparator **126**, only enabling sample-and-hold circuit **129** during post-conduction resonance. The blanking signal is represented by a waveform **205** and the output of blanking circuit **134** is represented by a waveform **206**.

There are numerous ways to generate blanking waveform **205**. In the illustrative example, sampling is enabled at time **T1** when the voltage at the feedback terminal **144** reaches substantially zero. The voltage at the output of sample-and-hold circuit **129** is offset by a small voltage **130** (**ΔV** of **Figure 2**). During the next switching cycle, the previously sampled (held) voltage is compared to the output voltage of integrator **128** by comparator **125**. Comparator **125** triggers sample-and-hold circuit **124**, which samples the feedback voltage at the output of the resistive divider formed by resistors **110**, **111** at time **Tfb**. Waveform **207** shows the timing of feedback voltage sampling by sample-and-hold circuit **124**. The sampled feedback voltage is compared to reference voltage **REF** by error amplifier **123**, which outputs an error signal that controls pulse width modulator circuit **105**.

Every switching cycle, the output of integrator **128** is reset to a constant voltage level Vreset by a reset pulse **203** in

order to remove integration errors. It is convenient to reset integrator **128** following time **T2**. However, in general, integrator **128** can be reset at any time with the exceptions of times **Tfb** and **T1** which are sampling times.

Since flyback transformer **101** (and inductor **198** in the circuit of **Figure 1B**) is fully de-energized every switching cycle, the output of integrator **128** represents a voltage analog of the magnetization current in the transformer **101** (and magnetization current of filter inductor **198** in the circuit of **Figure 1B**). Time **To** corresponds a point of zero magnetization current. Voltage offset **ΔV** sets a constant small from the actual secondary winding **142** zero-current point, and this a small offset in sampling time **Tfb**, at which the voltage at feedback terminal **144** is sampled. The technique described above eliminates the effect of most of the parasitic elements of the power supply, and substantial improvement of regulation of output voltage of the switching power converter is achieved.

A method and apparatus in accordance with an alternative embodiment of the present invention are included in traditional peak current mode controlled pulse width modulator circuit to form a circuit as depicted in **Figure 3**, wherein like reference designators are used to indicate like elements between the

circuit of Figures 1 and 3. Only differences between the circuits of Figures 1 and 3 will be described below.

Referring to **Figure 3**, since the output voltage of the integrator **128** is a representation of the magnetic flux in transformer **101**, integrator **128** output is an indication of current conducted through power switch **102**. Pulse width modulator circuit includes a pulse width modulator comparator **132** and a latch circuit **133**. In operation, when the output voltage of integrator **128** the output voltage of error amplifier **123**, comparator **132** resets latch **133** and turns off power switch **102**. Latch **133** is set with a fixed frequency **Clock** signal at the beginning of the next switching cycle, initiating the next turn-on of the switch **102**.

Figure 4 depicts a switching power converter in accordance with yet another embodiment of the present invention that is similar to the circuit of **Figure 3**, but is set up to operate in critically discontinuous (boundary) conduction mode of flyback transformer **101**. Unlike the power converter of **Figure 3**, which operates at a constant switching frequency determined by the frequency of the **Clock** signal, the circuit of **Figure 4** is free running. A free running operating mode is provided by connecting the output of blanking circuit **134** to the "S" (set) input of

latch **133**. Operation of the circuit of **Figure 4** is illustrated in the waveform diagrams of **Figure 5**. Referring to **Figures 6** and **7**, waveform **301** represents the voltage at feedback terminal **144**, waveform **302** shows the output voltage of the integrator circuit, and waveform **303** shows the **Reset** timing of the integrator **128**. The output of zero-derivative detect comparator **126** is depicted by waveform **304**. Waveforms **305**, **306** and **307** show the blanking **134**, the integrator sample-and-hold **129** and feedback sample-and-hold **124** timings, respectively. Operation of the power converter circuit of **Figure 4** is similar to the one of **Figure 3**, except that latch circuit **133** is reset by the output of blanking circuit **134**. The reset occurs when comparator **126** detects a zero-derivative condition in feedback terminal **144** output voltage **301** during post-conduction resonance. Therefore, power switch **102** is turned on after one half period of the post conduction resonance at the lowest possible voltage across switch **102**. The above-described "valley" switching technique minimizes power losses in switch **102** due to discharging of parasitic capacitance **146**. At the same time, the transformer **101** is operated in the boundary conduction mode, since the next switching cycle always starts immediately after the entire magnetization energy is transferred to the power supply output. Operating the transformer **101** in the critically discontinuous

conduction mode reduces power loss and improves the efficiency of the switching power converter of **Figure 4**.

Indirect current sensing by synthesizing a voltage corresponding to magnetization current (as performed in the control circuits of **Figures 3, 4** and **6**) enables construction of single stage power factor corrected (SS-PFC) switching power converters. One example of such an SS-PFC switching power converter is shown in **Figure 6.** The control circuit is identical to that of **Figure 4**, only the switching and input circuits differ. Common reference designators are used in Figures 4 and 6 and only differences will be described below.

The power converter of **Figure 6** includes a power transformer **101** with two primary windings **141**, two bulk energy storage capacitors **135** with a series connected diode **190**, in addition to all other elements of the power converter of **Figure 4**. The input voltage **VIN** is a full wave rectified input AC line voltage. In operation, referring to **Figures 5** and **6**, when power switch **102** is turned on at time **Ton**, the voltage **VIN** is applied across a boost inductor **136** via a diode **137**, causing a linear increase in the current through inductor **136**. At the same time, a substantially constant voltage from bulk energy storage capacitors **135** is applied across primary windings **141** causing

transformer **101** to store magnetization energy. Diode **190** is reversed-biased during this period. Between times **Ton** and **Toff**, power switch **102** conducts a superposition of magnetization currents of the transformer **101** and boost inductor **136**. Following time **Toff**, transformer **101** transfers its stored energy via diode **107** to capacitor **108** and load **109**. Simultaneously, boost inductor **136** transfers its energy to bulk energy storage capacitors **135** via primary windings **141** and forward biased diode **190**.

Boost inductor **136** is designed to operate in discontinuous conduction mode. Therefore, its magnetization current is proportional to the input voltage **VIN**, inherently providing good power factor performance, as the average input impedance has little or no reactive component. Diode **137** ensures discontinuous conduction of boost inductor **136** by blocking reverse current. A peak current mode control scheme that maintains peak current in power switch **102** in proportion to the output of voltage error amplifier **123**, is not generally desirable in the power converter of **Figure 6**. Since the current through power switch **102** is a superposition of the currents in boost inductor winding **136** and transformer primary windings **141**, keeping the power switch current proportional to the voltage error signal tends to distort the input current waveform.

In summary, with respect to the control circuit of **Figure 6**, the voltage error signal is made independent of the current in boost inductor **136**, while the voltage error signal set proportional to the magnetization current in the transformer **101**. Therefore, the switching power converter of **Figure 6** inherently provides good power factor performance. In addition, the above-described control circuit eliminates the need for direct current sensing. The method of the control circuit described above also provides an inherent output over-current protection when the voltage error signal is limited.

While the switching power converters of **Figures 4** and **6** eliminate the effect of most of the parasitics in a power converter, a small error in the output voltage regulation is still present due to series resistance (ESR) of output capacitor **108**. The current into the capacitor **108** is equal to (I2-Io) where I2 is current in secondary winding **142**, and Io is the output current of the switching power converter. The output voltage deviation from the average output voltage can be expressed as ESR*(I2-Io), where ESR is equivalent series resistance of capacitor **108**. The sampling error is represented by the deviation from the average output voltage at a time when I2 is zero. Therefore, the above-described error is equal to (-

Io*ESR). **Figure 7** depicts a compensation resistor **138** connected between the output of voltage error amplifier **123** and the output of the resistive divider formed by resistors **110**, **111**, which can be added to the switching power converters of **Figures 4** and **6** to cancel the above-described regulation error, since the voltage at the output of error amplifier **123** is representative of the power converter output current **Io**.

The circuit of **Figure 7** compensates for output voltage error due to ESR of capacitor **108** for a given duty ratio of power switch **102**. The value of resistor **138** is selected in inverse proportion to (1-D), where D is the duty ratio of the power switch **102**. When more accurate compensation is needed, a circuit as depicted in **Figure 8** may be implemented. The circuit of **Figure 8** includes a compensation resistor **138**, a low pass filter **139** and a chopper circuit **140**. In operation, chopper circuit **140** corrects the compensation current of resistor **138** by factor of (1-D), chopping the output voltage of error amplifier **123** using the inverting output signal of the pulse width modulator latch **133**. The switching component of the compensation signal is filtered using low pass filter **139**.

The present invention introduces a new method and apparatus for controlling output voltage of magnetically coupled isolated

switching power converters that eliminate a requirement for opto-feedback, current sense resistors and/or separate feedback transformers by selective sensing of magnetic flux. Further, the present invention provides high switching power converter efficiency by minimizing switching losses. The present invention is particularly useful in single-stage single-switch power factor corrected AC/DC converters due to the indirect current sensing technique of the present invention, but may be applied to other applications where the advantages of the present invention are desirable. While the illustrative examples include an auxiliary winding of a power transformer or output filter inductor for detecting magnetic flux and thereby determining a level of magnetic energy storage, the circuits depicted and claimed herein can alternatively derive their flux measurement from any winding of a power transformer or output filter inductor. Further, the measurement techniques may be applied to non-coupled designs where it may be desirable to detect the flux in an inductor that is discontinuously switched between an energizing state and a load transfer state.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made

therein without departing from the spirit and scope of the invention.